

**What have human experimental overfeeding studies taught us
about adipose tissue expansion and susceptibility to obesity and metabolic
complications?**

Daniel J Cuthbertson^{1,2}, Tom Steele¹, John P Wilding^{1,2}, Jason CG Halford³, Jo A
Harrold³, Mark Hamer⁴, Fredrik Karpe⁵.

¹Obesity and Endocrinology Research Group, University Hospital Aintree, UK,

²Institute of Ageing and Chronic Disease, University of Liverpool

³Psychological Sciences, Eleanor Rathbone Building, University of Liverpool,
Liverpool, L69 7ZA, UK

⁴National Centre for Sport & Exercise Medicine, Loughborough University

⁵Oxford Centre for Diabetes, Endocrinology & Metabolism

Running title: Overfeeding, adipose expansion and metabolic risk

Correspondence:

Dr. Daniel Cuthbertson

Obesity and Endocrinology Research Group,

University Hospital Aintree,

Lower Lane, Liverpool L9 7AL

Tel: +44 (0) 151 529 5911

Fax: +44 (0) 151 529 5888

E-mail: daniel.cuthbertson@liverpool.ac.uk

1 **Abstract**

2 Overfeeding experiments, in which we impose short-term positive energy balance,
3 help unravel the cellular, physiological and behavioural adaptations to nutrient excess.
4 These studies mimic longer-term mismatched energy expenditure and intake. There is
5 considerable inter-individual heterogeneity in the magnitude of weight gain when
6 exposed to similar relative caloric excess reflecting variable activation of
7 compensatory adaptive mechanisms. Significantly, given similar relative weight gain,
8 individuals maybe protected from/predisposed to metabolic complications (insulin
9 resistance, dyslipidaemia, hypertension), non-alcoholic fatty liver disease and
10 cardiovascular disease. Similar mechanistic considerations underpinning the
11 heterogeneity of overfeeding responses are pertinent in understanding emerging
12 metabolic phenotypes e.g. metabolically unhealthy normal weight and metabolically
13 healthy obesity.

14 Intrinsic and extrinsic factors modulate individuals' overfeeding response: intrinsic
15 factors include genetic/ethnic background, baseline metabolic health and regional fat
16 distribution; extrinsic factors include macronutrient (fat *vs.* carbohydrate) content,
17 fat/carbohydrate composition and overfeeding pattern (larger portions *vs.* snacks).

18 Subcutaneous adipose tissue (SAT) analysis, coupled with metabolic assessment, with
19 overfeeding have revealed how SAT remodels to accommodate excess nutrients.

20 Healthy remodeling involves adipocyte *hyperplasia*; dysfunctional remodeling
21 involves *hypertrophy* inducing inflammation and insulin resistance. Biological
22 responses of SAT also govern the extent of ectopic (visceral/liver) fat deposition.

23 Body composition analysis by DEXA/MRI have determined the relative expansion of
24 SAT (including abdominal/gluteofemoral SAT) *versus* ectopic fat with overfeeding.

25 Such studies have contributed to the *adipose expandability hypothesis* whereby SAT

1 has a finite capacity to expand (governed by intrinsic biological characteristics) and
2 once capacity is exceeded ectopic fat deposition occurs. The potential for SAT
3 expandability confers protection from/predisposes to the adverse metabolic responses
4 to over-feeding. The concept of a *personal fat threshold* suggests a large inter-
5 individual variation in SAT capacity with ectopic fat/metabolic decompensation once
6 one's own threshold is exceeded.

7 This review summarises insight gained from overfeeding studies regarding
8 susceptibility to obesity and related complications with nutrient excess.

9

10 **Introduction**

11 Long-term regulation and maintenance of body weight and body composition relies
12 upon integrated systems controlling energy intake, energy expenditure, substrate
13 utilisation and partitioning among different metabolic tissues and pathways.
14 Peripheral signals released from the gastrointestinal tract and adipose tissue integrate
15 within the hypothalamus to regulate energy intake and energy expenditure. Fat-free
16 mass, through the resting metabolic rate, also regulates energy intake. It has been
17 proposed that body weight is maintained at a 'set-point' and that deviations from this
18 point (with negative or positive energy balance) are countered and minimised by
19 feedback mechanisms involving compensatory changes in appetite and energy
20 expenditure^{1, 2}.

21 Obesity represents a state of energy imbalance created by mismatched energy
22 expenditure (reduced physical activity) and energy intake (nutrient excess). However,
23 individuals subjected to a similar relative positive energy balance show considerable
24 heterogeneity in the extent to which their body weight or body composition is altered.
25 Fat has the greatest storage capacity of the macronutrients; protein and carbohydrate

1 have a much lesser capacity. Thus, body weight change occurs predominantly via
2 alterations in adipose tissue volume with a much smaller contribution from changes in
3 lean body mass.

4 There is abundant information on weight loss (achieved in many different ways) but
5 much less information on controlled weight gain. Overfeeding experiments, in which
6 we mimic a short-term state of energy imbalance, have facilitated our understanding
7 of the adaptive cellular, physiological and behavioral responses of adipose tissue and
8 other organs (e.g. liver, skeletal muscle and brain) to weight gain and helped explain
9 the inter-individual heterogeneity to weight gain. These studies have also provided
10 insight into susceptibility to metabolic decompensation with weight gain.

11 This is a narrative review, however, to ensure all relevant literature is considered,
12 systematic searches were carried out on Medline and Scopus using the terms
13 “overfeeding”, “overeating”, “hypercaloric”, “controlled weight gain” and
14 “experimental weight gain” limited to English language papers with human subjects.
15 2272 abstracts were screened, with 168 articles reporting the effects of hypercaloric
16 diets in humans identified. This was supplemented by manual searches of reference
17 lists. Reports from important overfeeding studies are described in this review, with
18 data from experimental studies addressing the different baseline participant
19 characteristics, overfeeding regimes imposed and imaging techniques (Table 1),
20 effects on adipose tissue and ectopic fat distribution, adipocyte and metabolic
21 responses (Table 2) and on adipokines, gut hormones and appetite regulation (Table
22 3).

23

24 **Lessons learnt from early overfeeding studies**

1 Forty years ago, to understand the biological response of adipose tissue to weight gain
2 (hyperplasia vs. hypertrophy), Sims *et al* conducted a landmark overfeeding study in
3 inmates at Vermont State Prison³. He studied 5 lean individuals, with no family
4 history of obesity, and in exchange for early parole subjected them to 10 weeks of
5 supervised overfeeding while they remained sedentary. They were fed a diet of their
6 own choice consisting of a three-fold higher caloric intake than would be needed to
7 maintain body weight, aiming for 15-25% weight gain.

8 Underlying the significant mean weight gain was a considerable inter-individual
9 weight change between the inmates. The findings highlighted that the magnitude of
10 weight gain cannot be predicted from the magnitude of positive calorie balance, with
11 some individuals protected from, or predisposed to, weight gain through a variety of
12 mechanisms. The key finding was that fat mass expansion occurred via an increase in
13 adipocyte cell size rather than cell number *i.e.* adipocyte hypertrophy rather than
14 hyperplasia occurred.

15

16 **Genetic basis for fat distribution and metabolic health**

17 Body fat distribution appears intrinsic to the individual and is likely to depend on
18 heritable factors such as genetic variants, which are likely also subject to epigenetic
19 regulation. A recent study identified 49 genetic loci associated with waist-to-hip ratio
20 (adjusted for BMI), showing a stronger effect in women. These loci were enriched for
21 genes expressed in adipose tissue with pathway analysis implicating adipogenesis,
22 angiogenesis and insulin resistance as processes influencing fat distribution⁴.

23 Several recent publications have highlighted several specific (common) genetic
24 variants (particularly those associated with insulin resistance) where there is
25 dissociation between the body mass index (BMI) and the risk of type 2 diabetes

1 mellitus (T2DM) or cardiovascular disease (CVD) based on differing body
2 composition/regional fat distribution^{5, 6}. Genetic evidence has been provided for
3 normal weight/lower BMI individuals with a metabolically obese phenotype,
4 incorporating components of the metabolic syndrome and whose body composition is
5 characterised by greater hepatic steatosis and increased visceral adipose tissue (VAT)
6 relative to subcutaneous adipose tissue (SAT) (i.e. lower SAT capacity). These
7 individuals were at an increased risk of T2DM, coronary artery disease or
8 hypertension⁵. Conversely, genetic evidence has been provided for individuals with a
9 higher BMI but lower risk of T2DM, hypertension and CVD. Presence of these
10 ‘favourable adiposity alleles’ are associated with lower insulin levels and a higher
11 SAT:VAT ratio (i.e. higher SAT capacity)⁶.
12 The same genetic/epigenetic factors will also determine the pattern/distribution of fat
13 depot expansion during weight gain.

14

15 **Conceptual framework for fate of excess energy** (Figure 1)

16 With overfeeding, there are two fates for the surplus energy: either through
17 stimulation of energy expenditure or deposition in a storage depot (**Figure 1A**).
18 However, the majority of excess energy is stored, rather than expended; the amount
19 stored representing the difference between total energy expended and total energy
20 ingested. The surplus energy maybe stored in adipose tissue (**Figure 1B**) or as lean
21 body mass (**Figure 1C**). The biological properties of adipose tissue, and its response
22 to overfeeding, profoundly influence the distribution of body fat change: upper vs.
23 lower body fat *and* subcutaneous adipose tissue (SAT) vs. ectopic fat deposition
24 including as visceral adipose tissue (VAT) or liver fat (**Figure 1D**). The distribution

of excess body fat (whether stored as SAT, upper or lower body or as ectopic fat) has potentially profound secondary consequences on metabolic and cardiovascular risk.

Changes in energy expenditure with overfeeding (Figure 1A)

Total energy expenditure (TEE) is composed of resting energy expenditure (REE) (~60% of total), thermic effects of food and activity energy expenditure (exercise and non-exercise activity thermogenesis⁷).

TEE TEE is stimulated with overfeeding (by ~10%)⁸ but does not increase linearly with weight gain⁹. The extent of TEE stimulation during overfeeding governs the amount of excess energy stored and thus associated weight gain: individuals with a lesser tendency to gain weight increase TEE to a greater extent. With ensuing weight gain, resting metabolic rate will further increase (related to increased body mass) with recalibration dependent upon the relative changes in fat volume *vs.* muscle mass (skeletal muscle has higher relative energy requirements relative to adipose tissue)¹⁰.

The stimulation of REE also depends upon the macronutrient content of the overfeeding regime with a hierarchy of macronutrient oxidation; macronutrients with limited storage capacity are oxidized first. Fat overfeeding has minimal effect on fat oxidation and total energy expenditure, such that 90-95% of excess energy is stored, resulting in greater fat accumulation. In response to carbohydrate overfeeding, there is stimulation of carbohydrate oxidation and an increase in TEE with a lower proportion (75-85%) of energy stored². Prolonged overfeeding carbohydrate increases body fat by stimulation of *de novo lipogenesis* of hepatic and extra-hepatic (adipose tissue) origin. The predominant effect of protein overfeeding is accretion of lean body mass with the effect of increasing resting metabolic rate¹¹.

1 ***Diet-induced thermogenesis (DIT)*** DIT, the energy expenditure associated with
2 metabolising food, is also influenced by both the energy content and the
3 macronutrient composition of the food ingested: isocaloric amounts of protein,
4 carbohydrate and fat increase diet-induced energy expenditure by 20-30%, 5-10% and
5 0-3% of TEE respectively.

6 ***Activity energy expenditure (AEE)*** AEE is composed of energy expenditure related
7 to spontaneous physical activity and non-exercise activity thermogenesis (NEAT).
8 Differences in levels of NEAT have a greater impact on TEE than differences in
9 spontaneous physical activity. Obese individuals tend to undertake less NEAT than
10 lean individuals, being sedentary by a mean of 2 hours more per day⁷. NEAT has been
11 shown to have a role in resistance to weight gain: individual susceptibility to
12 overfeeding is determined by a variable induction in NEAT. 16 volunteers were
13 overfed 1,000 calories daily for 2 months, with a mean weight gain of 10lb, but with a
14 range of 2-16lb. Change in NEAT (kcal/day) was inversely correlated with fat gain
15 (kg). Those with a high NEAT response were more protected from obesity with
16 overfeeding; those with a low NEAT response were more susceptible to obesity with
17 overfeeding⁷.

18

19 **Storage of excess energy (Figure 1B, C, D)**

20 Weight gain during overfeeding cannot be oversimplified by assuming 3,500 calories
21 equates to a 1lb/0.45kg change in body weight, even if the energy surplus during
22 overfeeding is accurately quantified. This erroneous assumption is based upon the
23 premise that body weight changes reflect primarily loss or gain of adipose tissue
24 (comprising 87% triglyceride), knowing the energy density of fat to be 9 kcal/g.
25 Longer term changes in body fat are accompanied by changes in lean tissue whose

1 metabolisable energy density is significantly less than body fat (4 kcal/g). Increased
2 lean body mass would increase REE and higher body weight increases the energy
3 requirement of physical activity. Mathematical models of energy expenditure and
4 weight change have been developed that reflect the dynamic changes in body
5 composition as weight increases¹⁰.

6 A number of overfeeding studies have been performed with concomitant assessment
7 of body composition by DEXA, CT and/or MRI to provide insight into which storage
8 depot the excess energy is partitioned. Table 1 details the baseline participant
9 characteristics and overfeeding regime used in overfeeding studies summarising those
10 using concomitant assessment of body composition (*DEXA ± MRI*) to determine fate
11 of excess energy into regional fat depots, with results summarized in Table 2.

12 ***Storage in adipose tissue vs. in lean body mass*** The concept of energy partitioning
13 relates to the proportion of excess energy that is directed towards lean tissue vs. fat
14 with the energy partition ratio being a non-linear function of body fat. People with a
15 higher initial body fat have a greater fraction of their weight change attributable to
16 increases in body fat vs. lean tissue¹².

17 ***Storage in upper body (abdominal) vs. lower body (gluteofemoral) fat.*** The regional
18 distribution of SAT, quantified by DEXA, is critically important with subcutaneous
19 fat depots in upper and lower body characterized by different structural and functional
20 differences and therefore associated with different metabolic risk. Abdominal SAT
21 (ASAT), i.e. upper body fat, is characterized by high uptake of diet-derived fat and a
22 high lipid turnover. In contrast, gluteofemoral fat (GFAT) has a reduced lipid
23 turnover but a high capacity to accommodate fat undergoing redistribution^{13, 14}.

24 Accumulation of adipose tissue in the upper body (abdominal obesity) is associated
25 with increased risk of development of insulin resistance, type 2 diabetes mellitus and

1 higher cardiovascular and total mortality, independent of BMI. Indeed, individuals
2 with a normal BMI and abdominal obesity (determined by waist-hip ratio) have a
3 higher mortality compared with either individuals with a normal BMI without central
4 obesity or with all overweight or obese individuals (based on BMI)¹⁵. Conversely,
5 accumulation of fat in the lower body (gluteofemoral obesity) shows opposite
6 associations with cardiovascular disease and type 2 diabetes mellitus when adjusted
7 for overall fat mass. Paradoxically lower body fat accumulation is associated with
8 improved cardiovascular and metabolic profiles (protective role) suggested to
9 sequester lipids that would be destined for ectopic fat deposition¹⁶.

10 Lower and upper body fat stores show a different response to weight gain reflecting
11 their different biological characteristics and capacity for lipid storage/turnover¹³.

12 ***Storage in subcutaneous adipose tissue vs. ectopic fat deposition (visceral adipose***
13 ***tissue and liver)*** Subcutaneous adipose tissue (SAT) must undergo expansion to
14 accommodate increased lipid supply to avoid deposition of lipids/fatty acids in non-
15 adipocyte cells (causing lipotoxicity)¹⁷. SAT expansion may occur by two distinct
16 mechanisms: *hypertrophy* of existing adipocytes or promotion of differentiation of
17 pre-adipocytes (*hyperplasia*).

18 The *adipose tissue expandability hypothesis* has suggested capacity for AT expansion
19 is determined by functional adipocyte characteristics and their molecular and
20 biochemical adaptive responses to positive energy balance¹⁸. This capacity is limited
21 and determines the propensity for excess lipids to be orientated to other tissues *i.e.*
22 ectopic lipid deposition, with secondary lipotoxicity. Taylor *et al.*, proposed a large
23 inter-individual variation in the SAT buffering capacity with each individual having a
24 *personal fat threshold*¹⁹. This means that once the SAT storage capacity is reached,
25 ectopic fat deposition ensues with associated lipotoxicity and metabolic dysfunction.

1 These concepts of a finite AT expandability, which has large intra-individual
2 variation, may explain the distinct body composition phenotypes of metabolic healthy
3 and unhealthy, lean or obese²⁰. Body composition analysis from these individuals
4 have confirmed that metabolically unhealthy normal weight individuals are
5 characterised by a low capacity for SAT expandability (*low personal fat threshold*)
6 hence their higher lipid deposition in other organs (resulting in a higher VAT:SAT
7 ratio and higher liver fat)²¹. Conversely, metabolically healthy obese individuals are
8 characterised by a high capacity for SAT expandability (*high personal fat threshold*)
9 (a lower VAT:SAT ratio and lower liver fat content)²⁰.
10 Insights from transgenic mice (lacking leptin while overexpressing adiponectin)
11 demonstrate that massive expansion of SAT is metabolically inert, providing a safe
12 harbor for potentially toxic lipids, with reduced ectopic fat (e.g. liver and visceral fat)
13 and preserved insulin sensitivity with little/no systemic inflammation²². In contrast, a
14 reduced capacity for SAT expansion is associated with subsequent inflammatory
15 consequences, development of systemic insulin resistance (IR) and metabolic
16 syndrome (MS), associated with subsequent development of endothelial dysfunction
17 and atherosclerosis. These findings are borne out by observations in people with
18 generalised lipodystrophy, who have limited capacity for subcutaneous fat storage and
19 consequently develop severe insulin resistance, NAFLD and dyslipidaemia²³.
20 Conversely, the PPAR γ agonists thiazolidinediones improve metabolic profiles by
21 promoting adipogenesis and increasing fat mass²⁴.

22

23 **Healthy and dysfunctional adipose tissue remodeling and metabolic**
24 **consequences**

1 Healthy AT remodeling involves all cellular components of adipose tissue and not just
2 adipocytes, with induction of various pathways within adipose tissue including that of
3 lipid metabolism, the renin-angiotensin pathway, angiogenesis and extracellular
4 matrix²⁵. ‘Healthy’ SAT expansion consists of *hyperplasia*, AT enlargement through
5 recruitment of adipogenic precursor cells, stimulation of angiogenesis and remodeling
6 of the extracellular matrix (ECM); ‘unhealthy’ SAT expansion consists of adipocyte
7 *hypertrophy* with limited angiogenesis and hypoxia resulting in secondary changes
8 involving induction of tissue fibrosis²⁶, adipocyte cell death and enhanced pro-
9 inflammatory cytokine secretion²⁷. During this process there is a phenotypic switch
10 with an infiltration of pro-inflammatory (M1) macrophages from the anti-
11 inflammatory (M2) phenotype²⁸.

12 A number of overfeeding studies have tested the validity of the adipose tissue
13 expandability hypothesis by concomitantly examining changes in adipose tissue
14 (morphology, gene and protein expression), body composition (using DEXA and/or
15 MRI/¹H-MRS) and the metabolic consequences (using oral glucose tolerance test or
16 euglycaemic clamps) (summarised in Table 2). Thus we are able to simultaneously
17 examine adaptations of the adipocytes structurally (e.g. adipocyte cell size, number
18 and size distribution) and functionally (e.g. changes in expression of lipid metabolism
19 genes) coupled with regional fat responses and partitioning of fat into different tissues
20 (SAT vs. ectopic deposition). Such studies have provided mechanistic insight into
21 how dysfunctional SAT remodeling contributes to visceral and liver fat deposition
22 (clinically as non-alcoholic fatty liver disease, NAFLD) and in doing so initiating
23 metabolic dysfunction with development of components of metabolic syndrome
24 (dyslipidaemia, hypertension, insulin resistance).

25 Alligier *et al.* overfed participants an additional daily lipid mixture composed of 70g

1 (760 kcal) of saturated and monounsaturated fatty acids for 56 days²⁹. Mean body
2 weight change was 2.5 kg with substantial inter-individual heterogeneity in magnitude
3 of weight gain and in the relative accretion of subcutaneous *vs.* visceral fat. Although
4 the increment in SAT was associated with the increase in body weight, there was no
5 relationship between the increment in body weight and VAT nor was there any
6 association between the expansion of SAT and VAT volumes. The magnitude of the
7 increase in VAT volume was positively correlated with the magnitude of the post-
8 prandial exogenous fatty acid release in the circulation during a labelled palmitate test
9 meal. Using SAT gene expression data, individuals with a high visceral fat gain
10 appear to have reduced induction of expression of genes involved in triglyceride
11 synthesis and lipid storage suggesting a reduced SAT lipid storage capacity in these
12 individuals.

13 Testing this hypothesis further Fabbrini *et al.* overfed obese individuals who were
14 either metabolically healthy *vs.* unhealthy³⁰. It was hypothesised that the
15 metabolically healthy obese (MHO) will be resistant, whereas the metabolically
16 abnormal (MAO), will be prone to the adverse metabolic effects of overfeeding.
17 Employing stable isotopes, the results demonstrated that metabolically healthy obese,
18 but not metabolically unhealthy obese, were protected from the adverse metabolic
19 effects from weight gain with no change in hepatic and peripheral insulin sensitivity
20 or in VLDL-TG secretion rates with overfeeding. This was related to upregulation of
21 biological pathways and genes associated with AT lipogenesis in MHO, but not in
22 MAO subjects. In contrast, McLaughlin *et al.*, tested the hypothesis in obese, insulin-
23 sensitive (IS) *vs.* obese insulin-resistant (IR) individuals postulating similarly that the
24 IS subjects would demonstrate an adaptive adipose cell/tissue and metabolic
25 response. To the contrary, they found that IS, but not IR, subjects had greater

1 increases in VAT and liver fat and had a greater metabolic decompensation with
2 overfeeding³¹. This metabolic decompensation was correlated with smaller baseline
3 adipocyte size, greater adipocyte enlargement and decreased expression of lipid
4 metabolism genes. Previously it was thought that adipocyte enlargement occurred due
5 to increased triglyceride storage but the simultaneously reduced expression of lipid
6 metabolism genes as cells enlarge suggests this was not the case. Rather, as with the
7 study by Johannsen *et al.*³², the influence of the baseline adipocyte cell size on
8 worsening metabolic profiles suggest that adipocyte hypertrophy reflects impaired
9 adipocyte differentiation faced with increased fat storage requirements. The
10 explanation for these discrepant (and possibly counterintuitive) results are not clear,
11 as the baseline characteristics of the two groups of study participants were not hugely
12 dissimilar.

13 Votruba *et al.*, also investigated whether baseline insulin sensitivity could predict the
14 pattern of weight change, hypothesising that insulin resistant individuals would accrue
15 more abdominal subcutaneous or visceral fat whereas insulin sensitive individuals
16 would accrue leg fat. No relationship was found between baseline insulin sensitivity
17 and the pattern of regional fat distribution in response to overfeeding³³.

19 **Intrinsic factors influencing the response to overfeeding**

20 A number of studies highlight a significant genetic pre-disposition to the the relative
21 amount and distribution of fat mass with overfeeding:

22 *Twin studies* Several twin studies have provided strong evidence that genetic factors
23 significantly contribute to the individual differences in the sensitivity to alterations in
24 energy balance. In the Quebec feeding study 12 pairs of monozygotic twins were
25 overfed by 1000 kcal, six days a week for 84 days with a mean weight gain of 8.1kg

1 (2.7kg lean body mass). Although the range of weight gain between the twin pairs
2 was staggering (4.3-13.3kg) with no correlation between the total energy ingested and
3 weight gained, there was a high degree of concordance within each twin pair between
4 the amount of weight gained and the distribution of excess energy³⁴.

5 *Family history of type 2 diabetes mellitus (T2DM)* Healthy individuals with a family
6 history of T2DM are predisposed to the adverse effects of overfeeding. The response
7 to overfeeding was studied in 41 sedentary individuals with and without a family
8 history of T2DM (FH+ and FH- respectively). FH+ individuals gained more weight
9 and became more insulin resistant³⁵.

10 *Ethnicity* It is well established that South Asians are more susceptible to central
11 obesity and cardiometabolic consequences³⁶. This maybe explained by their
12 phenotype of higher fat mass and lower lean mass, contributing to insulin resistance³⁷,
13 ³⁸. Overfeeding experiments with a short-term, high fat diet in South Asians vs.
14 Caucasians has shown a more detrimental effect on the metabolic profile^{39, 40}.

15 ***Effect of low birth weight*** Individuals with a low birth weight, despite their
16 increased risk of insulin resistance when exposed to a high fat diet, did not differ
17 in their AT response compared with control subjects⁴¹.

18 *Participant characteristics* Inter-individual differences in baseline characteristics
19 explain varying weight change with factors such as low basal metabolic rate, lower
20 baseline lipid oxidation (higher respiratory quotient, RQ), lower levels of spontaneous
21 physical activity predisposing individuals to greater weight gain⁴². Baseline body
22 weight and amount of body fat also determine the magnitude of the weight change
23 and even for the same increment in energy intake these differ in lean and obese
24 people.

25

1 **Extrinsic factors influencing the response to overfeeding**

2 *Overfeeding regime characteristics* The duration, energy density and the
3 macronutrient composition of the overfeeding regime influences the response to
4 overfeeding.

5 *Effects of macronutrients* A key consideration is the macronutrient composition of
6 overfeeding and whether the effects differ depending on whether excess calories arise
7 from high-fat, high-carbohydrate or a combination of both. This is particularly
8 pertinent with conflicting public health messages about the relative merits and perils
9 of high-fat or high-carbohydrate diets. Surprisingly, few studies have compared
10 overfeeding regimens based on these macronutrients. Two studies characterised the
11 effects of overfeeding with high fat vs. high carbohydrate diet on energy storage. Both
12 showed comparable weight gain, however, Horton *et al* showed dietary fat to lead to
13 greater fat accumulation than carbohydrate, whereas Lammert *et al* found there was
14 no difference in fat storage based on macronutrient, explained by carbohydrates
15 inducing hepatic and extrahepatic lipogenesis^{2, 43}. Two small, short term studies have
16 found fat and carbohydrate overfeeding to have similar effects on liver fat, however
17 comprehensive assessment including molecular biology techniques and metabolic
18 end-points is lacking

19 ^{44, 45}. Bray *et al.* recently compared overfeeding regimes with different levels of
20 dietary protein, finding the low protein group showed a greater increase in % body fat,
21 but a decrease in intrahepatic lipid⁴⁶.

22 *Influence of dietary fat composition* In the LIPOGAIN study Rosqvist *et al.*, overfed
23 healthy individuals muffins with either polyunsaturated fatty acids (PUFA) or
24 saturated fatty acids (SFA) and demonstrated distinct effects on the magnitude and
25 distribution of fat deposition and on lean tissue⁴⁷. With the PUFA diet equal amounts

1 of fat and lean tissue were added; in contrast, with a SFA diet four times as much fat
2 as lean tissue was added.

3 *Influence of dietary carbohydrate composition* There has been interest in comparing
4 the effects of different sugars on metabolic health, especially given a proposed link of
5 excess fructose consumption with non-alcoholic fatty liver disease⁴⁸. A small number
6 of studies have compared fructose and glucose overfeeding. Two meta-analyses called
7 for more data but found no difference in either lipid profile or ectopic fat deposits
8 between different carbohydrate sources^{49, 50}.

9 *Influence of pattern of feeding* The effects of overfeeding differ according to the
10 frequency and timing of the food intake. Overeating by consuming frequent meals
11 (i.e. snacking) rather than isocaloric, large meals differentially affects the
12 accumulation of intra-abdominal and liver fat⁵¹.

13

14 **Effects of overfeeding on other tissues/organs.**

15 *Skeletal muscle* Effects in skeletal muscle have been examined and as in adipose
16 tissue there is evidence of induction of extracellular matrix remodeling, inflammation,
17 reduced insulin signaling and insulin resistance^{27, 52}.

18 *Cardiovascular system* Increasing BMI is clearly linked with increasing risk of
19 CVD⁵³ although individuals with metabolically healthy obesity may have some
20 protection against it⁵⁴. Similarly, normal weight individuals who are metabolically
21 unhealthy (MUNW) also maybe at increased CV risk¹⁵. Cross-sectional mechanistic
22 data involving detailed body composition and echocardiography shows that
23 subclinical measures of systolic and diastolic myocardial performance are related to
24 fat distribution and metabolic health rather than simply fat mass²¹. Metabolically
25 healthy individuals, whether lean or obese, with lower VAT and liver fat have

1 preserved myocardial function compared with lean or obese, metabolically unhealthy
2 individuals²¹.

4 **Effects of overfeeding on appetite and gut hormone regulation**

5 Consistent with the concept of a weight ‘set point’, it has been speculated that a
6 period of overfeeding may be accompanied by subsequent compensatory changes in
7 peripheral signals from the gut or expanded adipose tissue mass that would help
8 normalise body weight. Despite this there are few studies that have characterised
9 alterations in the circulating levels of gut hormones or adipokines in response to
10 overfeeding, nor to the modulation of appetite. The design, participants and results of
11 these studies are summarized in Table 3.

12 Cornier *et al.*, examined activation of key brain regions in response to visual food
13 cues (control images, neutral hedonic value and high hedonic value food items) using
14 functional MRI (fMRI). They studied participants after two days of eucaloric energy
15 intake, followed by two days of overfeeding with 30% excess energy intake
16 consumed. There was significant attenuation of the effect of the high hedonic value
17 images after two days of overfeeding. Satiety ratings were also higher and hunger
18 ratings lower after the overfeeding⁵⁵. When comparing thin and reduced-obese
19 individuals, the attenuation of the activation of brain regions by high hedonic value
20 images after overfeeding was not observed in the reduced-obese individuals
21 suggesting a propensity to gain weight⁵⁶. Gut hormone responses have also been
22 examined with conflicting results (Table 3).

24 **Interaction of overfeeding with changes in physical activity**

Few studies have examined the interaction of changes in physical activity with overfeeding. Knudsen *et al.*, implemented a 14 day overfeeding protocol (total energy intake increased by ~50%) combined with physical inactivity (step reduction to 1,500 steps/day) in healthy young men⁵⁷. Changes in insulin sensitivity were apparent prior to changes in body composition measured by DEXA/MRI⁵⁷. Wahlin implemented a similar protocol for 7 days, with an overconsumption of 50% excess energy simultaneously restricting the physical activity to below 4,000 steps, and similarly noted a dramatic reduction in insulin sensitivity with modulation of key metabolic genes (e.g. SREBP1c and FAS) and protein expression (GLUT4, AMPK, AKT1 and AKT2) within adipose tissue⁵⁸. Significantly, the same short-term overfeeding and reduced physical activity protocol, with inclusion of 45 min of daily treadmill running at 70% maximal oxygen uptake, counteracted most of the detrimental effects at a whole-body and adipose tissue level, despite the provision of additional dietary energy intake to account for the extra energy expended by exercise⁵⁸.

Conclusions and future lines of research

The challenge with the current obesity epidemic is to understand how to facilitate healthy AT remodeling expansion with hyperplasia, involving adipocyte differentiation, rather than dysfunctional AT remodeling with hypertrophy, induction of insulin resistance and inflammation. In doing so we can reduce ectopic fat and potentially ectopic fat-related complications, T2DM, NAFLD and CVD. Prediction of personal fat thresholds would help individuals maintain their metabolic health as long as possible. Overfeeding studies using drugs that cause SAT proliferation (e.g. thiazolidinediones) to facilitate healthy AT expansion and partition excess lipid in the SAT may provide useful insight. This review has highlighted the paucity of knowledge regarding adipose tissue, metabolic and cardiovascular responses to excess

1 calories from fat vs. carbohydrate intake. This area is a major concern for public
2 health and appropriate dietary recommendations and is a knowledge void that needs
3 filling.

4

5

6 **Conflict of Interest**

7 The authors declare no conflict of interest.

1 **References**

- 2 1. Sumithran P, Prendergast LA, Delbridge E, Purcell K, Shulkes A, Kriketos A
3 *et al.* Long-term persistence of hormonal adaptations to weight loss. *N Engl J*
4 *Med* 2011; **365**(17): 1597-604.
- 5
- 6 2. Horton TJ, Drougas H, Brachey A, Reed GW, Peters JC, Hill JO. Fat and
7 carbohydrate overfeeding in humans: different effects on energy storage. *Am J*
8 *Clin Nutr* 1995; **62**(1): 19-29.
- 9
- 10 3. Salans LB, Horton ES, Sims EA. Experimental obesity in man: cellular
11 character of the adipose tissue. *J Clin Invest* 1971; **50**(5): 1005-11.
- 12
- 13 4. Shungin D, Winkler TW, Croteau-Chonka DC, Ferreira T, Locke AE, Mägi R
14 *et al.* New genetic loci link adipose and insulin biology to body fat
15 distribution. *Nature* 2015; **518**(7538): 187-96.
- 16
- 17 5. Yaghootkar H, Scott RA, White CC, Zhang W, Speliotes E, Munroe PB *et al.*
18 Genetic evidence for a normal-weight "metabolically obese" phenotype
19 linking insulin resistance, hypertension, coronary artery disease, and type 2
20 diabetes. *Diabetes* 2014; **63**(12): 4369-77.
- 21
- 22 6. Yaghootkar H, Lotta LA, Tyrrell J, Smit RA, Jones SE, Donnelly L *et al.*
23 Genetic evidence for a link between favorable adiposity and lower risk of type
24 2 diabetes, hypertension and heart disease. *Diabetes* 2016.
- 25

- 1 7. Levine JA, Lanningham-Foster LM, McCrady SK, Krizan AC, Olson LR,
2 Kane PH *et al.* Interindividual variation in posture allocation: possible role in
3 human obesity. *Science* 2005; **307**(5709): 584-6.
4
- 5 8. Diaz EO, Prentice AM, Goldberg GR, Murgatroyd PR, Coward WA.
6 Metabolic response to experimental overfeeding in lean and overweight
7 healthy volunteers. *The American journal of clinical nutrition* 1992; **56**(4):
8 641-55.
9
- 10 9. Harris AM, Jensen MD, Levine JA. Weekly changes in basal metabolic rate
11 with eight weeks of overfeeding. *Obesity (Silver Spring)* 2006; **14**(4): 690-5.
12
- 13 10. Hall KD, Sacks G, Chandramohan D, Chow CC, Wang YC, Gortmaker SL *et al.*
14 Quantification of the effect of energy imbalance on bodyweight. *Lancet*
15 2011; **378**(9793): 826-37.
16
- 17 11. Bray GA, Smith SR, de Jonge L, Xie H, Rood J, Martin CK *et al.* Effect of
18 dietary protein content on weight gain, energy expenditure, and body
19 composition during overeating: a randomized controlled trial. *Journal of*
20 *American Medical Association* 2012; **307**(1): 47-55.
21
- 22 12. Hall K. Modeling Metabolic Adaptations and Energy Regulation in Humans.
23 *Annual Review Nutrition* 2012; **32**: 35-54.
24

- 1 13. Tchoukalova YD, Votruba SB, Tchkonina T, Giorgadze N, Kirkland JL, Jensen
2 MD. Regional differences in cellular mechanisms of adipose tissue gain with
3 overfeeding. *Proceedings of the National Academy of Sciences of the United*
4 *States of America* 2010; **107**(42): 18226-31.
- 5
- 6 14. Pinnick KE, Nicholson G, Manolopoulos KN, McQuaid SE, Valet P, Frayn
7 KN *et al.* Distinct developmental profile of lower-body adipose tissue defines
8 resistance against obesity-associated metabolic complications. *Diabetes* 2014;
9 **63**(11): 3785-97.
- 10
- 11 15. Sahakyan KR, Somers VK, Rodriguez-Escudero JP, Hodge DO, Carter RE,
12 Sochor O *et al.* Normal-Weight Central Obesity: Implications for Total and
13 Cardiovascular Mortality. *Ann Intern Med* 2015; **163**(11): 827-35.
- 14
- 15 16. Karpe F, Pinnick KE. Biology of upper-body and lower-body adipose tissue-
16 link to whole-body phenotypes. *Nat Rev Endocrinol* 2014; **11**(2): 90-100.
- 17
- 18 17. Rutkowski JM, Stern JH, Scherer PE. The cell biology of fat expansion.
19 *Journal of Cell Biology* 2015; **208**(5)(1540-8140): 501-512.
- 20
- 21 18. Gray SL, Vidal-Puig AJ. Adipose tissue expandability in the maintenance of
22 metabolic homeostasis. *Nutrition Reviews* 2007; **65**(6): S7-12.
- 23
- 24 19. Taylor R, Holman RR. Normal weight individuals who develop type 2
25 diabetes: the personal fat threshold. *Clin Sci (Lond)* 2015; **128**(7): 405-10.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

20. Stefan N, Kantartzis K, Machann J, Schick F, Thamer C, Rittig K *et al.* Identification and characterization of metabolically benign obesity in humans. *Arch Intern Med* 2008; **168**(15): 1609-16.
21. Dobson R, Burgess MI, Sprung VS, Irwin A, Hamer M, Jones J *et al.* Metabolically healthy and unhealthy obesity: differential effects on myocardial function according to metabolic syndrome, rather than obesity. *Int J Obes (Lond)* 2016; **40**(1): 153-61.
22. Kim JY, van de Wall E, Laplante M, Azzara A, Trujillo ME, Hofmann SM *et al.* Obesity-associated improvements in metabolic profile through expansion of adipose tissue. *J Clin Invest* 2007; **117**(9): 2621-37.
23. Garg A. Acquired and inherited lipodystrophies. *N Engl J Med* 2004; **350**(12): 1220-34.
24. Spiegelman BM. PPAR-gamma: adipogenic regulator and thiazolidinedione receptor. *Diabetes* 1998; **47**(4): 507-514.
25. Alligier M, Meugnier E, Debard C, Lambert-Porcheron S, Chanseume E, Sothier M *et al.* Subcutaneous adipose tissue remodeling during the initial phase of weight gain induced by overfeeding in humans. *The Journal of clinical endocrinology and metabolism* 2012; **97**(2): E183-92.

- 1 26. Kos K, Wong S, Tan B, Gummesson A, Jernas M, Franck N *et al.* Regulation
2 of the fibrosis and angiogenesis promoter SPARC/osteonectin in human
3 adipose tissue by weight change, leptin, insulin, and glucose. *Diabetes* 2009;
4 **58**(8): 1780-8.
- 5
- 6 27. Tam CS, Covington JD, Bajpeyi S, Tchoukalova Y, Burk D, Johannsen DL *et*
7 *al.* Weight gain reveals dramatic increases in skeletal muscle extracellular
8 matrix remodeling. *The Journal of clinical endocrinology and metabolism*
9 2014; **99**(5): 1749-57.
- 10
- 11 28. Lumeng CN, Bodzin JL, Saltiel AR. Obesity induces a phenotypic switch in
12 adipose tissue macrophage polarization. *The Journal of clinical investigation*
13 2007; **117**(1): 175-84.
- 14
- 15 29. Alligier M, Gabert L, Meugnier E, Lambert-Porcheron S, Chanseaux E,
16 Pilleul F *et al.* Visceral fat accumulation during lipid overfeeding is related to
17 subcutaneous adipose tissue characteristics in healthy men. *The Journal of*
18 *clinical endocrinology and metabolism* 2013; **98**(2): 802-10.
- 19
- 20 30. Fabbrini E, Yoshino J, Yoshino M, Magkos F, Tiemann Luecking C,
21 Samovski D *et al.* Metabolically normal obese people are protected from
22 adverse effects following weight gain. *J Clin Invest* 2015; **125**(2): 787-95.
- 23
- 24 31. McLaughlin T, Craig C, Liu L-F, Perelman D, Allister C, Spielman D *et al.*
25 Adipose Cell Size and Regional Fat Deposition as Predictors of Metabolic

- 1 Response to Overfeeding in Insulin-Resistant and Insulin-Sensitive Humans.
2 *Diabetes* 2016; **65(5)**: 1245-54.
3
- 4 32. Johannsen DL, Tchoukalova Y, Tam CS, Covington JD, Xie W, Schwarz JM
5 *et al.* Effect of Eight Weeks of Overfeeding on Ectopic Fat Deposition and
6 Insulin Sensitivity: Testing the "Adipose Tissue Expandability" Hypothesis.
7 *Diabetes Care* 2014; **37(10)**: 2789-97.
8
- 9 33. Votruba SB, Jensen MD. Insulin sensitivity and regional fat gain in response
10 to overfeeding. *Obesity (Silver Spring)* 2011; **19(2)**: 269-75.
11
- 12 34. Bouchard C, Tremblay A, Després J-P, Nadeau A, Lupien PJ, Thériault G *et*
13 *al.* The Response to Long-Term Overfeeding in Identical Twins. *New England*
14 *Journal of Medicine* 1990; **322(21)**: 1477-1482.
15
- 16 35. Samocha-Bonet D, Campbell LV, Viardot A, Freund J, Tam CS, Greenfield
17 JR *et al.* A family history of type 2 diabetes increases risk factors associated
18 with overfeeding. *Diabetologia* 2010; **53(8)**: 1700-8.
19
- 20 36. Sniderman AD, Bhopal R, Prabhakaran D, Sarrafzadegan N, Tchernof A. Why
21 might South Asians be so susceptible to central obesity and its atherogenic
22 consequences? The adipose tissue overflow hypothesis. *Int J Epidemiol* 2007;
23 **36(1)**: 220-5.
24

- 1 37. Lear SA, Humphries KH, Kohli S, Chockalingam A, Frohlich JJ, Birmingham
2 CL. Visceral adipose tissue accumulation differs according to ethnic
3 background: results of the Multicultural Community Health Assessment Trial
4 (M-CHAT). *Am J Clin Nutr* 2007; **86(2)**: 353-9.
5
- 6 38. Lear SA, Kohli S, Bondy GP, Tchernof A, Sniderman AD. Ethnic variation in
7 fat and lean body mass and the association with insulin resistance. *J Clin*
8 *Endocrinol Metab* 2009; **94(12)**: 4696-702.
9
- 10 39. Wulan SN, Westerterp KR, Plasqui G. Metabolic profile before and after
11 short-term overfeeding with a high-fat diet: a comparison between South
12 Asian and White men. *Br J Nutr* 2014; **111(10)**: 1853-61.
13
- 14 40. Wulan SN, Schrauwen-Hinderling VB, Westerterp KR, Plasqui G. Liver fat
15 accumulation in response to overfeeding with a high-fat diet: a comparison
16 between South Asian and Caucasian men. *Nutrition & Metabolism* 2015;
17 **12(1)**: 1-9.
18
- 19 41. Gillberg L, Perfilyev A, Brons C, Thomasen M, Grunnet LG, Volkov P *et al.*
20 Adipose tissue transcriptomics and epigenomics in low birthweight men and
21 controls: role of high-fat overfeeding. *Diabetologia* 2016; **59(4)**: 799-812.
22
- 23 42. Galgani J, Ravussin E. Energy metabolism, fuel selection and body weight
24 regulation. *Int J Obes (Lond)* 2008; **32(Suppl 7)**: S109-19.
25

- 1 43. Lammert O, Grunnet N, Faber P, Bjornsbo KS, Dich J, Larsen LO *et al.*
2 Effects of isoenergetic overfeeding of either carbohydrate or fat in young men.
3 *Br J Nutr* 2000; **84**(2): 233-45.
4
- 5 44. Sobrecases H, Le KA, Bortolotti M, Schneiter P, Ith M, Kreis R *et al.* Effects
6 of short-term overfeeding with fructose, fat and fructose plus fat on plasma
7 and hepatic lipids in healthy men. *Diabetes Metab* 2010; **36**(3): 244-6.
8
- 9 45. Lecoultre V, Egli L, Carrel G, Theytaz F, Kreis R, Schneiter P *et al.* Effects of
10 fructose and glucose overfeeding on hepatic insulin sensitivity and
11 intrahepatic lipids in healthy humans. *Obesity (Silver Spring)* 2013; **21**(4):
12 782-5.
13
- 14 46. Bray GA, Redman LM, de Jonge L, Rood J, Smith SR. Effect of three levels
15 of dietary protein on metabolic phenotype of healthy individuals with 8 weeks
16 of overfeeding. *J Clin Endocrinol Metab* 2016; **101**(7): 2836-43.
17
- 18 47. Rosqvist F, Iggman D, Kullberg J, Cedernaes J, Johansson HE, Larsson A *et*
19 *al.* Overfeeding polyunsaturated and saturated fat causes distinct effects on
20 liver and visceral fat accumulation in humans. *Diabetes* 2014; **63**(7): 2356-68.
21
- 22 48. Chiu S, Sievenpiper JL, de Souza RJ, Cozma AI, Mirrahimi A, Carleton AJ *et*
23 *al.* Effect of fructose on markers of non-alcoholic fatty liver disease
24 (NAFLD): a systematic review and meta-analysis of controlled feeding trials.
25 *Eur J Clin Nutr* 2014; **68**(4): 416-23.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

49. Ma J, Karlsen MC, Chung M, Jacques PF, Saltzman E, Smith CE *et al.* Potential link between excess added sugar intake and ectopic fat: a systematic review of randomized controlled trials. *Nutr Rev* 2016; **74**(1): 18-32.
50. Chiavaroli L, de Souza RJ, Ha V, Cozma AI, Mirrahimi A, Wang DD *et al.* Effect of Fructose on Established Lipid Targets: A Systematic Review and Meta-Analysis of Controlled Feeding Trials. *J Am Heart Assoc* 2015; **4**(9): e001700.
51. Koopman KE, Caan MW, Nederveen AJ, Pels A, Ackermans MT, Fliers E *et al.* Hypercaloric diets with increased meal frequency, but not meal size, increase intrahepatic triglycerides: a randomized controlled trial. *Hepatology* 2014; **60**(2): 545-53.
52. Seyssel K, Alligier M, Meugnier E, Chanseume E, Loizon E, Canto C *et al.* Regulation of Energy Metabolism and Mitochondrial Function in Skeletal Muscle during Lipid Overfeeding in Healthy Men. *J Clin Endocrinol Metab* 2014; **99**(7): 1254-62.
53. Calle EE, Thun MJ, Petrelli JM, Rodriguez C, Heath CWJ. Body-Mass Index and Mortality in a Prospective Cohort of U.S. Adults. *New England Journal of Medicine* 2008; **341**: 1097-1105.

- 1 54. Hamer M, Stamatakis E. Metabolically healthy obesity and risk of all-cause
2 and cardiovascular disease mortality. *J Clin Endocrinol Metab* 2012; **97**(7):
3 2482-8.
- 4
- 5 55. Cornier MA, Von Kaenel SS, Bessesen DH, Tregellas JR. Effects of
6 overfeeding on the neuronal response to visual food cues. *The American*
7 *journal of clinical nutrition* 2007; **86**(4): 965-71.
- 8
- 9 56. Cornier MA, Salzberg AK, Endly DC, Bessesen DH, Rojas DC, Tregellas JR.
10 The effects of overfeeding on the neuronal response to visual food cues in thin
11 and reduced-obese individuals. *PLoS One* 2009; **4**(7): e6310.
- 12
- 13 57. Knudsen SH, Hansen LS, Pedersen M, Dejgaard T, Hansen J, Hall GV *et al.*
14 Changes in insulin sensitivity precede changes in body composition during 14
15 days of step reduction combined with overfeeding in healthy young men.
16 *Journal of applied physiology* 2012; **113**(1): 7-15.
- 17
- 18 58. Walhin JP, Richardson JD, Betts JA, Thompson D. Exercise counteracts the
19 effects of short-term overfeeding and reduced physical activity independent of
20 energy imbalance in healthy young men. *The Journal of physiology* 2013;
21 **591**(Pt 24): 6231-43.
- 22
- 23 59. van der Meer RW, Hammer S, Lamb HJ, Frolich M, Diamant M, Rijzewijk LJ
24 *et al.* Effects of short-term high-fat, high-energy diet on hepatic and

- 1 myocardial triglyceride content in healthy men. *The Journal of clinical*
2 *endocrinology and metabolism* 2008; **93**(7): 2702-8.
- 3
- 4 60. Sevastianova K, Santos A, Kotronen A, Hakkarainen A, Makkonen J, Silander
5 K *et al.* Effect of short-term carbohydrate overfeeding and long-term weight
6 loss on liver fat in overweight humans. *The American journal of clinical*
7 *nutrition* 2012; **96**(4): 727-34.
- 8
- 9 61. Boon MR, Bakker LE, Haks MC, Quinten E, Schaart G, Van Beek L *et al.*
10 Short-term high-fat diet increases macrophage markers in skeletal muscle
11 accompanied by impaired insulin signalling in healthy male subjects. *Clinical*
12 *science* 2015; **128**(2): 143-51.
- 13
- 14 62. Cornier MA, Grunwald GK, Johnson SL, Bessesen DH. Effects of short-term
15 overfeeding on hunger, satiety, and energy intake in thin and reduced-obese
16 individuals. *Appetite* 2004; **43**(3): 253-9.
- 17
- 18 63. Jebb SA, Siervo M, Fruhbeck G, Goldberg GR, Murgatroyd PR, Prentice AM.
19 Variability of appetite control mechanisms in response to 9 weeks of
20 progressive overfeeding in humans. *Int J Obes (Lond)* 2006; **30**(7): 1160-2.
- 21
- 22 64. Cahill F, Shea JL, Randell E, Vasdev S, Sun G. Serum peptide YY in response
23 to short-term overfeeding in young men. *The American journal of clinical*
24 *nutrition* 2011; **93**(4): 741-7.
- 25

- 1 65. Wadden D, Cahill F, Amini P, Randell E, Vasdev S, Yi Y *et al.* Serum
2 acylated ghrelin concentrations in response to short-term overfeeding in
3 normal weight, overweight, and obese men. *PloS one* 2012; **7**(9): e45748.
4
- 5 66. Wadden D, Cahill F, Amini P, Randell E, Vasdev S, Yi Y *et al.* Circulating
6 glucagon-like peptide-1 increases in response to short-term overfeeding in
7 men. *Nutr Metab (Lond)* 2013; **10**(1): 33.
8
- 9 67. Germain N, Galusca B, Caron-Dorval D, Martin JF, Pujos-Guillot E, Boirie Y
10 *et al.* Specific appetite, energetic and metabolomics responses to fat
11 overfeeding in resistant-to-bodyweight-gain constitutional thinness. *Nutr*
12 *Diabetes* 2014; **4**: e126.
13
- 14 68. Apolzan JW, Bray GA, Smith SR, de Jonge L, Rood J, Han H *et al.* Effects of
15 weight gain induced by controlled overfeeding on physical activity. *Am J*
16 *Physiol Endocrinol Metab* 2014; **307**(11): E1030-7.
17
18
19
20
21
22
23
24
25

1 **Figure legends**

2

3 **Table 1** Overview of feeding studies detailing baseline participant characteristics and
4 overfeeding regime summarising those using concomitant assessment of body
5 composition (*DEXA ± MRI ± CT*) to determine fate of excess energy into regional fat
6 depots. F Fat; CHO Carbohydrate; NAFLD Non-Alcoholic Fatty Liver Disease.

7

8 **Table 2** Key studies examining adipose tissue deposition, changes in adipose tissue
9 structure/biology and metabolic consequences following overfeeding. IHTG
10 Intrahepatic triglycerides; TG Triglycerides; HOMA-IR Homeostatic Model
11 Assessment- Insulin Resistance; NEFA Non-esterified Fatty Acids; SAT
12 Subcutaneous Adipose Tissue; AUC Area Under Curve; FFA Free Fatty Acids;
13 VLDL Very Low Density Lipoproteins; IMCL Intramyocellular Lipids; IS Insulin
14 Sensitivity

15

16 **Table 3** Key studies examining changes in appetite or circulating levels of
17 adipokines/gut hormones in response to overfeeding. CHO Carbohydrate; F Fat; P
18 Protein; VAS Visual Analogue Scales; fMRI functional Magnetic Resonance
19 Imaging; PYY Peptide YY; GLP-1 Glucagon-like peptide-1.

20

21 **Figure 1** Conceptual framework highlighting potential mechanisms where inter-
22 individual differences in partitioning of excess energy with overfeeding may arise.
23 Inter-individual differences may arise due to **A**) proportion of excess energy expended
24 *vs.* excess energy stored, **B**) relative storage in adipose tissue *vs.* in lean body mass,
25 **C**) relative storage in upper body *vs.* lower body fat, **D**) amount of ectopic fat

1 deposition in visceral adipose tissue (VAT), liver or other organs (skeletal muscle,
2 heart or pancreas etc.).

3

4 **Figure 2** The relationship between BMI and insulin sensitivity is not linear as
5 suggested by epidemiological evidence. Rather individuals are susceptible to
6 metabolic decompensation when their weight exceeds their '*personal fat threshold*'.
7 This threshold varies hugely: those with a low 'personal fat threshold' are more
8 susceptible to cardio-metabolic decompensation with only modest weight gain
9 (metabolically unhealthy normal weight) *vs.* a higher threshold means individuals can
10 withstand much greater weight gain without decompensating (metabolically healthy
11 obese) (adapted from Taylor *et al.*¹⁹).

Table 1

Reference	Baseline characteristics	Mean Age (y)	Mean BMI (kg/m ²)	Overfeeding regime	Period	Activity	Body composition analysis modality
Van der Meer <i>et al.</i> 2008 ⁵⁹	15 healthy men	25±6.6	23.4±2.5	Normal diet + 2632 kcal/d; 94% F	3 days	Free living	Cardiac and liver ¹ H-MRS
Tchoukalova <i>et al.</i> 2010 ¹³ and Votruba <i>et al.</i> ³⁰	28 healthy men (n=15), women (n=13)	NR	22.1±0.5	Tailored to achieve 5% weight gain	56 days	Free living	DEXA CT at L2/3, L3/4 and L4/5.
Sevastianova <i>et al.</i> 2012 ⁶⁰	17 non-diabetic males (n=5), females (n=11) (56% with NAFLD)	Median 54 (40-59)	30.6±1.2	Normal diet + 1000kcal/d; 98% CHO	21 days	Free living	Abdominal MRI (T1-weighted) Liver ¹ H-MRS
Alligier <i>et al.</i> 2012,2013 ^{25,29}	44 healthy men	33±1	NR (range 18-30)	Regular diet + 760kcal/d; 91% F	56 days	Usual	DEXA Abdominal MRI (T1-weighted)
Knudsen <i>et al.</i> 2012 ⁵⁷	9 healthy men	24±3.3	21.6±2.5	Usual diet + 1500kcal as snack packages	14 days	Step reduction <1500 steps/day (10278±2399 to 1521±488)	DEXA/Abdominal MRI
Koopman <i>et al.</i> 2014 ⁵¹	36 healthy men, 4 groups: HFHS-S n=8 HFHS-F n=8 HS-S n=10 HS-F n=10	22.6±2.9 21.5±1.9 22±2.5 21.9±2.8	22.3±1 22.5±1.5 21.7±1.1 22.6±1.8	140% BL requirement: increased meal size (S) or frequency (F). Two supplements: High Fat High Sugar (HFHS): 49% CHO, 35% F, 16% P High Sugar (HS): Commercial sucrose drinks.	42 days	Free living	Abdominal MRI (T1-weighted) Liver ¹ H-MRS
Johannsen <i>et al.</i> 2014 ³²	29 healthy men	26.8±5.4	25.5±2.3	1.4X BL energy requirement; 41% CHO, 44% F, 15% P.	56 days	Free living	Abdominal MRI (T1-weighted) ¹ H-MRS of liver and soleus muscle
Rosqvist <i>et al.</i> 2014 ⁴⁷	39 healthy subjects: PUFA intervention: 5 women, 13 men SFA intervention: 6 women, 13 men	PUFA: 26.7±4.6 SFA: 27.1±3.6	PUFA: 20.8 (19.5-23.1) SFA: 19.9 (18.9-20.7)	Regular diet + muffins (51% F, 5% P, 44% CHO) titrate to weight gain supplemented with polyunsaturated (PUFA) or saturated (SFA) fat	49 days	Usual	Abdominal MRI ¹ H-MRS liver Pancreatic MRS
Fabbrini <i>et al.</i> 2015 ³⁰	20 obese subjects: Metabolically normal (MNO; IHTG <5.6%) n=12 Metabolically abnormal (MAO; IHTG >10%) n=8	MNO: 43±10 MAO: 52±7	MNO: 34.0±3.0 MAO: 35.7±3.9	Regular diet +1000kcal/d maintaining macronutrient intake. Delivered via specific menu choices from fast food chains.	Until 5-7% weight gain; mean 52 days	Free living	Abdominal MRI (T1-weighted) Liver ¹ H-MRS
Boon <i>et al.</i> 2015 ⁶¹	24 healthy men	22.1±0.4	21.5±0.4	Regular diet +1275kcal/d; 94% F	5 days	No physical activity	Liver ¹ H-MRS
McLaughlin <i>et al.</i> 2016 ³¹	15 insulin-sensitive 16 insulin resistant	54 ±8 57±6	29.3±2.4 30.7±2.7	Regular diet+ snacks/beverages Mean additional calories 880 kcal/d (50% CHO, 35% fat, 15% protein) Target weight gain 3.2 kg (0.8kg/week)	28 days	Free living	CT measured SAT, VAT and mid-thigh fat Liver ¹ H-MRS

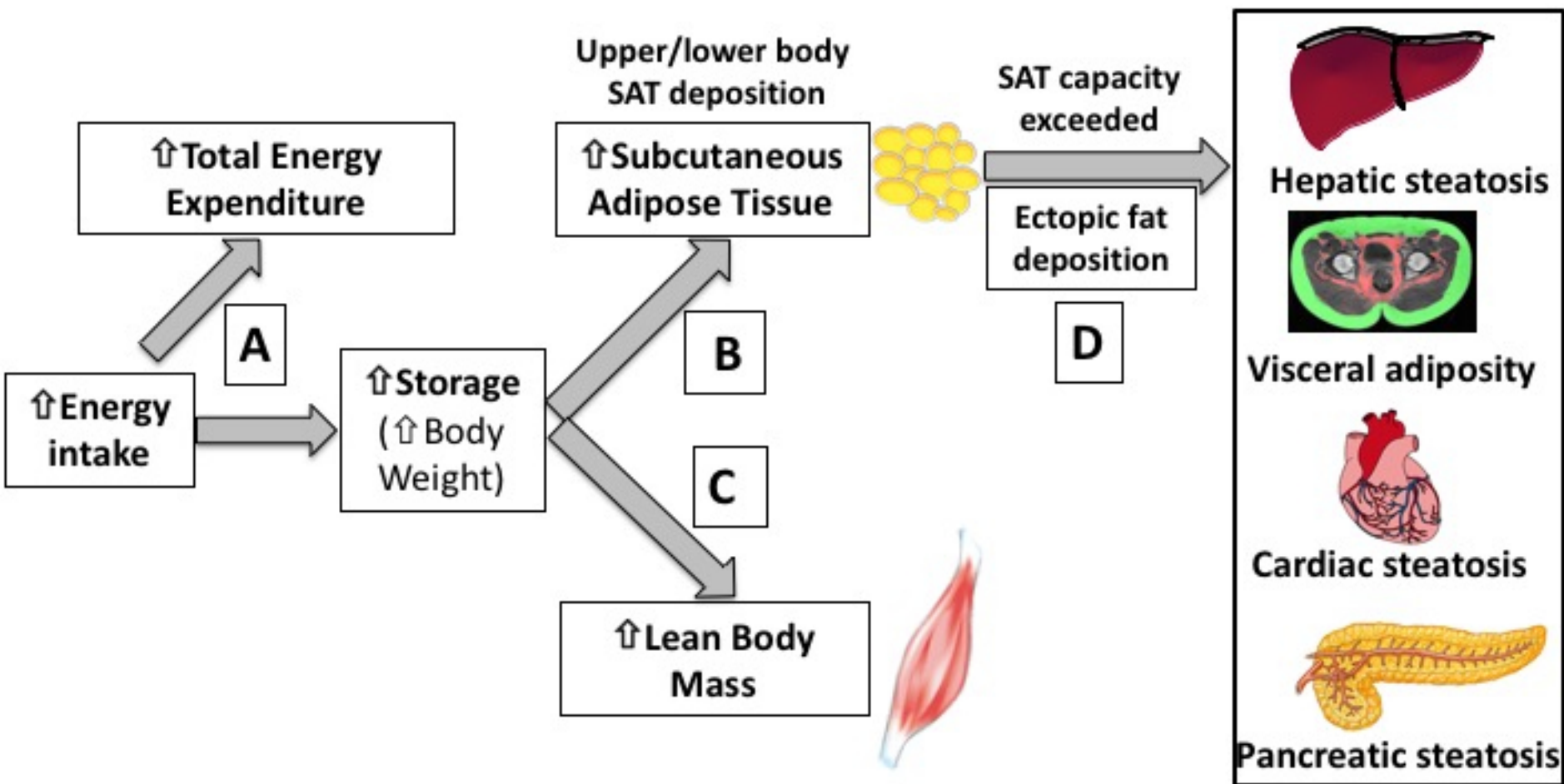
Table 2

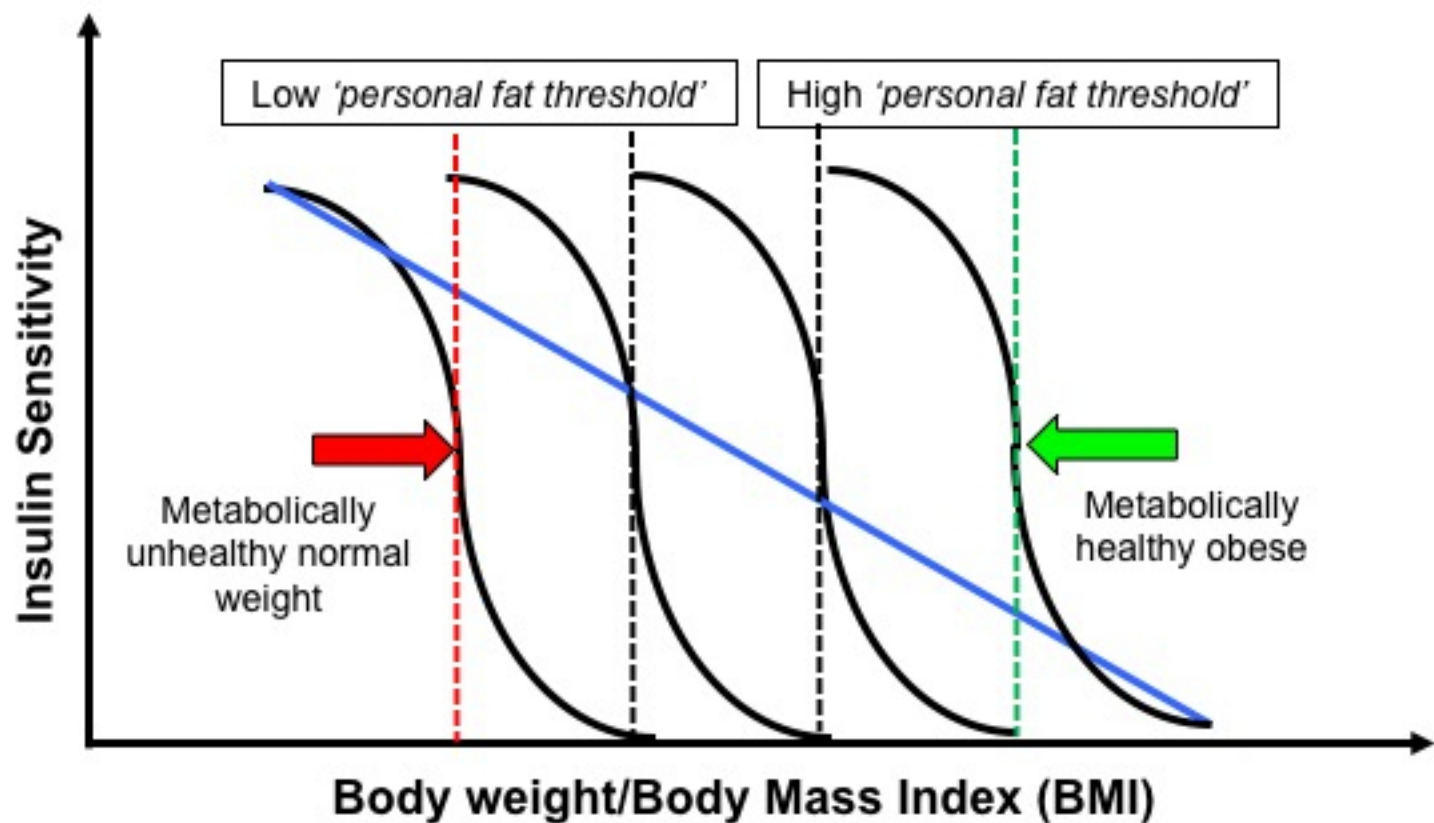
Reference	Weight gain (kg)	Changes in fat distribution			Adipocyte response	Metabolic response		Key findings
		Changes in SAT	Changes in VAT	Changes in liver fat		Insulin Sensitivity	Lipid levels	
Van der Meer <i>et al.</i> 2008 ⁵⁹	BMI increased 23.4±2.5 to 23.6±2.5	NR	NR	IHTG: 2.01±1.79% to 4.26±2.78% Cardiac TG: 0.38±0.18% to 0.4±0.12%)	NA	HOMA 2.0±1.2 to 4.9±2.3	TG 1.3±0.4 to 2.9±1.1mmol/L NEFA 0.54±0.29 to 0.92±0.33mmol/L	NA
Tchoukolava <i>et al</i> 2010 ¹³ and Votruba <i>et al.</i> ³⁰	4.6±2.2kg	Upper body: +22.0±2.6% (women) +41.0±7.3% (men) Lower body: +18.2±1.3% (women) +34.9±5% (men)	+40.5%±5.8	NA	Femoral/abdo SAT Size (µg lipid/cell): Abdo: +39±11% Femoral: ±12±8% No. (x10⁶): Upper body: +3±5% Lower body: +23±7%	24 Insulin AUC Increased by 2685±6252 (p=0.04).	NA	Abdominal SAT adipocyte size correlated with upper- body fat gain. No correlation between between baseline insulin sensitivity and upper body SAT or VAT gain.
Sevastianova <i>et al.</i> , 2012 ⁶⁰	1.8±0.3kg (88.7±4.1 to 90.5±4.1kg)	4440 (3700-6210) to 4570 (4000-6280)cm ³	2180±300 to 2290±310cm ³	IHTG: 9.2±1.9% to 11.7±1.9%	NA	HOMA-IR 1.7±0.3 to 1.8±0.2	TG 1.1±0.11 to 1.4±0.12; FFA 424±31 to 416±38 Lipogenic index 16:0/18:2n-6 ratio: TG 2.1 (1.9-2.3) to 2.6 (2.4-4.1) VLDL 2.1±0.3 to 3.2±0.5	Increase in liver fat proportionate to de novo lipogenesis
Alligier <i>et al</i> 2012,2013 ^{25, 29}	2.5kg 79.1±1.8 to 81.6±1.8kg	91±7 to 100±7cm ³	92±11 to 102±11cm ³	NA	Abdominal SAT Size (cell surface µm2) 3123±129 to 3120±160 Number (cells/mm²) 320±16 to 336±28	HOMA-IR 2.29±0.16 to 2.44±0.15	FFA (µM) 418±23 to 355±16	NA
Knudsen <i>et al</i> 2012 ⁵⁷	1.6kg 71.3±3.5 to 72.9±3.4kg	NA	28.8±13.5 to 43.1±20.5cm ³	NA	NA	HOMA-IR 1.1 to 1.6 OGTT AUC increased 37±10% Clamp: glucose infusion rate reduced by 43.6±11%. Matsuda index reduced by 26±14%	TG 0.92 (0.64-1.3) to 1.13 (0.89-1.43) mM FFA 362.5(267.5- 491.2) to 233.4 (138.5-393.1) µM	Reduction in insulin sensitivity precedes changes in body composition.
Koopman <i>et al</i> 2014 ⁵¹	POOLED HFHS/HS-S: BMI 22.05±0.98 to 22.75±1.04 POOLED HFHS/HS-F: BMI 22.5±1.5 to 23.2±1.6	POOLED HFHS/HS-S: 0.225±0.06 to 0.228±0.056L POOLED HFHS/HS-F: 0.276±0.111 to 0.315±0.115L	0.196±0.068 to 0.215±0.041L 0.239±0.073 to 0.266±0.077L	Pooled HFHS/HS-S: IHTG: 0.83±0.38 to 1.00±0.78% Pooled HFHS/HS-F: IHTG: 1.22±0.93 to 2.18±1.9%	NA	Clamp: no change in peripheral insulin sensitivity.	TG significantly increased in HFHS-F group only (0.56±0.21 to 0.84±0.32mmol/L)	Hypercaloric diet with increased meal frequency increased intrahepatic fat independent of body weight gain and caloric content.
Johannsen <i>et al</i> 2014 ³²	+7.6±2.1kg (81.9±10.3 to 89.5±9.4kg)	Abdominal SAT: +1.3kg (4.1±1.5 to 5.4±1.8kg)	Abdominal VAT: +0.36kg (0.58±0.49 to 0.94±0.58kg)	IHTG: 1.5±0.6 to 2.19±1% IMCL: 0.45±0.24% to 0.49±0.24%	NA	Clamp (glucose infusion rate): Low dose insulin: +18% High dose insulin: +5% EGP suppression: 96±10% to 82±20%	TG (mg/dL) 87±42 to 96±68	Smaller adipocyte size associated with a greater decrease in insulin sensitivity. No association between adipocyte size and ectopic fat
Rosqvist <i>et al</i> 2014 ⁴⁷	PUFA 1.6±0.85kg (BL 67.4kg) SFA 1.6±0.96kg (BL 63.3kg)	Abdominal SAT: PUFA +0.25±0.32L (baseline: 2.2L) SFA +0.34±0.23L (baseline: 1.8L)	PUFA +0.11±0.21L (baseline 0.99L) SFA +0.22±0.16L (baseline: 0.81L)	IHTG: PUFA +0.04±0.24% (baseline 0.75%) SFA +0.56±1% (baseline 0.96%)	NA	HOMA-IR: PUFA +0.2±0.5 (baseline 1.23) SFA +0.18±0.3 (baseline 1.04)	NA	Changes in IHTG and VAT associated with changes in palmitic acid (SFA). Linoleic acid (PUFA) inversely associated with liver fat.

Fabbrini <i>et al</i> 2015 ³⁰	MNO: +6%; 95.8±13.7 to 101.7±14.4kg MAO: +6%; 103±11 to 109±11.6kg	MNO: +2%; (3008±796 to 3071±809cm) MAO: +5%; 3145±871 to 3308±928cm ³	MNO: +12%; 885±240 to 987±295cm ³ MAO: +12%; 1714±585 to 1912±645cm ³	IHTG MNO: 2.4±1.1 to 3.9±2.6% MAO: 15.2±4 to 22.8±4.3%	NA	HOMA-IR: MNO: +10% (baseline 2) MAO: +22% (baseline 6) Clamp: Suppression of glucose rate of appearance lower in MAO group.	TG (mg/dl): MNO: 0% (89±43 to 89±32) MAO +27% (134±61 to 170±52) VLDL apoB100: secretion increased in MAO but not MNO (p=0.004)	Transcriptional pathways related to lipid metabolism and synthesis: upregulated in metabolically healthy but not in metabolically unhealthy
Boon <i>et al</i> 2015 ⁶¹	69.1±1.9 to 69.6±1.9kg	NA	NA	IHTG: 1.57±0.27% to 3.43±0.49%	NA	HOMA-IR: 1.62±0.26 to 2.39±0.32	TG (mmol/l): 1.0±0.1 to 1.0±0.1 NEFA (mmol/l) 0.5±0.03 to 0.5±0.03	NA
McLaughlin <i>et al</i> 2016 ³¹	IS 86.2±10.1 to 89.6 ±10.3 IR 89.4±11.2 to 92.1±11.1	IS: 147 ± 54 to 162 ± 51cm ³ IR: 140 ± 34 to 148 ± 37cm ³	IS: 37±22 to 44±28cm ³ IR: 64±16 to 73±27cm ³	IHTG: IS: 0.03 ± 0.21 to 0.07 ± 0.04 IHTG: IR: 0.23±0.31 to 0.3±0.22	Abdominal SAT size and structure: Peak adipocyte diameter increased significantly only in IS subgroup. Significant decrease in percentage of small adipose cells in IS	Muscle insulin resistance worsened in IS group only: 45%(IS) vs. 8%(IR)	Insulin suppression of lipolysis worsened significantly in the IS subgroup alone	Smaller adipocyte size associated with a greater decrease in insulin sensitivity. IS rather than IR subjects experienced metabolic decompensation than IS subjects.

Table 3

Reference	Baseline characteristics	Mean Age (y)	Mean BMI (kg/m ²)	Dietary protocol	Period	Activity	Changes in appetite	Changes in gut hormones
Cornier et al, 2004 ⁶²	13 thin (7 women, 6 men) and 9 reduced obese (RO; 5 women, 4 men) subjects. RO group underwent period of 10% weight loss then 4 weeks weight stability before overfeeding.	Thin: 30.6±8 (women) 29.3±7.6 (men). RO: 38.2±8.3 (women), 36.5±7.05 (men)	Thin: 20.6±1.8 (women) 21.3±3 (men). RO: 30.4±2.6 (women), 27.5±1.8 (men)	Eucaloric diet for 7 days followed by 50% overfeeding (50% CHO, 30% F, 20% P).	7 days eucaloric intake, 3 days overfeeding	Habitual physical activity	VAS: pre-meal hunger reduced in thin but not RO group following OF. Post meal satiety increased in thin but not RO group following OF. Ad libitum energy intake: following OF non-significantly reduced in all.	N/A
Jebb et al, 2006 ⁶³	6 non-obese men	43.3 ± 10.6	21.9 ± 1.3	Overfeeding periods (+20%, +40%, +60% energy intake with fat) followed by free diet	3 x 3weeks	Habitual physical activity	Food intake stimulated overall during free diet period. Variable change with 'compensators' and 'non-compensators'.	Leptin elevated (+116%)
Cornier et al, 2007 ⁶⁵	25 healthy men (n=12), women (n=13)	35.6 ± 6.2y vs. 33.8 ± 4.7y	21.0 ± 1.3 vs. 22 ± 1.9	2 days eucaloric energy intake followed by 2 days overfeeding with 30% above eucaloric needs	2 days eucaloric intake, 2 days overfeeding	Habitual physical activity	fMRI response to visual food cues (<i>high hedonic value > neutral hedonic value</i>) blunted by overfeeding. VAS: reduced hunger and increased satiety ratings.	N/A
Cahill et al., 2011 ⁶⁴	69 young men			70% more calories than required (15% protein, 35% fat and 50% carbohydrate	1 week	Not reported	N/A	Serum PYY concentration significantly increased in response to overfeeding
Wadden et al., 2012 ⁶⁵	68 young men (normal weight, n=26; overweight, n=14; obese, n=28)	23 ± 0.4y	25.6 ± 0.6	70% more calories than required (15% protein, 35% fat and 50% carbohydrate	1 week	Not reported	N/A	Fasting serum acylated ghrelin increased in all groups in response to overfeeding
Wadden et al., 2013 ⁶⁶	72 healthy young men (normal weight n=30; overweight n=14; obese n=28)	23.11 ± 0.37	25.27 ± 0.56	70% more calories than required (15% protein, 35% fat and 50% carbohydrate	1 week	Not reported	N/A	Fasting GLP-1 increased in all groups with no difference based on weight status
Germain et al., 2014 ⁶⁷	8 constitutionally thin (CT) women (BMI <17.5 with no eating disorder or nutritional deficiency) and 8 normal weight controls	21.6±1.9 vs 22.1±0.8	17.1±0.3 vs 22.1±0.3	630kcal excess from fat (peanuts, cheese, olive oil, butter).	4 weeks	Habitual physical activity	N/A	Incremental AUC for PYY and GLP-1 unchanged in CT group and decreased in normal weight group after overfeeding. Fasting ghrelin increased after overfeeding, lower in CT group vs normal weight.
Apolzan et al 2014 ⁶⁸	15 men and 5 women. 1 normal weight, 8 overweight, 11 obese, otherwise healthy	34±9	30.7±4.6	140% energy requirements. 3 diets: High fat/low energy density (HF/LED; 1.05kcal/g; 50% F, 35% CHO, 15% P), high fat/high energy density (HF/HED; 1.6kcal/g; 50% F, 35% CHO, 15% P), high carbohydrate/low energy density (HC/LED; 1.05kcal/g; 20% F, 65% CHO, 15% P)	3 arm cross over design: 2 days OF with 4 days measurement of ad libitum intake	Physical activity tailored so energy expenditure stable over study period.	Ad libitum intake higher on first day following OF compared with others. Trend towards lower than baseline ad libitum intake following OF (significant only in HF/LED group). VAS: decreased hunger and increased satiety following HF/LED overfeeding only.	N/A





— Epidemiological hypothesis of linear relationship between BMI and insulin sensitivity

--- Individual's 'personal fat threshold'